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Indian Standard

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(पहला पुनरीक्षण)

Criteria for Structural Design of Reinforced Concrete Natural Draught Cooling Towers

(First Revision)

ICS 91.080.40

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Special Structures Sectional Committee, CED 38

FOREWORD

This Indian Standard (First Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Special Structures Sectional Committee had been approved by the Civil Engineering Division Council.

Reinforced concrete cooling towers are extensively used in thermal power stations and other heavy industries, such as steel plants. This standard is intended to provide unified approach for analysis, design and construction considerations of hyperbolic cooling towers, giving basic data regarding various loads and their design provisions.

This standard was first published in 1985. The standard has been revised based on the latest technical knowledge and experience gained from construction of cooling towers during past three decades. In this revision, the following major modifications have been effected:

a) Provisions on wind loading are given in detail.

b) Total and minimum pressure coefficients for calculation of wind pressure are given in detail.

c) Provision on interference effect of other structures in close vicinity has been added.

d) Clauses on temperature loading with respect to operations, environmental conditions and serviceability conditions are added.

e) Construction and shrinkage loads have been included.

f) New load combination for both ultimate and serviceability limit states have been given.

g) For design of tower shells, provisions on shell analysis and shell buckling have been modified.

Provisions of this standard are also applicable to cooling towers of other shapes formed by conic sections. However, structural studies carried out elsewhere on ellipsoidal, truncated conic, cylindrical and hyperboloid shell show that the hyperboloid offers substantial material economies compared to other shapes. The hyperboloid shell is, therefore, recommended at present for cooling tower shells.

The Committee responsible for the formulation of this standard has taken into consideration the need for international coordination among standards prevailing in different countries of the world. These considerations have led the Committee to derive assistance from the following:

a) Structural design of cooling towers, VGB Guidelines, 2010.

b) BS 4485 : Part 4 : 1996 Water cooling towers — Code of practice for structural design and construction.

c) EN 1991-1-5 : 2003(E) 2003- Actions on structures, Part 1-5 — General actions - thermal actions

The composition of the Committee responsible for the in the formulation of this standard is given in Annex C.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

CRITERIA FOR STRUCTURAL DESIGN OF REINFORCED CONCRETE NATURAL DRAUGHT COOLING TOWERS

(First Revision)

1 SCOPE

1.1 This standard essentially deals with the safety concepts, structural design and construction considerations of cast *in-situ* reinforced concrete hyperbolic natural draught cooling tower shells. Provisions of this standard may be applied to all common cooling tower shapes formed by conic sections.

1.2 The requirements of number, size, structural layout, location and spacing of towers arising out of thermal design considerations are not covered in this standard.

1.3 This standard also does not deal with the packing material, types, water distribution system and the method of testing the performance requirements of cooling towers.

1.4 Provisions of IS 2210 and IS 2204 shall also apply to the design and construction of cooling tower shells wherever they are not covered in this standard.

2 REFERENCES

The standards listed in Annex A contain provision which through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreement based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated therein.

3 TERMINOLOGY

For the purpose of this standard, the following definitions shall apply.

3.1 Basin Sill Level — Top level of the basin wall and this is taken as the datum level for the cooling towers.

3.2 Cold Water Basin — Device that underlies the tower to receive cooled water from the packing. This is also known as basin or pond.

3.3 Nominal Tower Dimensions — Dimensions used to indicate the effective size of cooling tower. In horizontal plane these are inner diameters and in vertical plane the height above the basin kerb level.

3.4 Packing Support Structure — Structure of beams and columns in concrete, which supports the packing material, distribution pipe work or flumes and drift eliminators. This is also known as internal structure or fill supporting structure.

3.5 Ring Beam — Thickened lowermost part of the shell immediately surrounding the shell support columns, spanning the column heads.

3.6 Shell — The part of a natural draught cooling tower, above the air inlet.

3.7 Shell Support Column — Inclined column or wall which spans the air intake opening and transmits the dead load of the shell, and any forces induced in it, to the foundation. These columns are also known as raker columns.

3.8 Shell Support Node — Junction between a pair of shell support columns and the ring beam.

3.9 Sump — Lowered portion of the cold water basin floor for draining. This is also known as basin sump or pond sump.

4 SYMBOLS

For the purpose of this standard, the following letter symbols shall have the meaning indicated against each:

a	Distance between cooling tower and cooling tower or cooling tower and corner of building. The distance shall be measured between centres of cooling towers or between centre of cooling tower and corner of the building.
a_R	Distance between wind ribs.
$c_{p,\theta}$	Total pressure coefficient.
c_f	Aerodynamic resistance coefficient.
d_m	Average diameter of the shell.
d_u	Diameter of shell at lower edge.
d_T	Shell diameter at throat, in m.

D	Base diameter at basin sill level.
DL	Dead load.
E_c	Short term static modulus of elasticity of concrete as per IS 456, in N/mm^2.
EQ	Earthquake load.
F	Wind load amplification factor including dynamic amplification and interference effects.
F_a	Dynamic amplification factor for shells with and without stiffening ribs.
F_i	Interference factor.
F_S	Foundation settlement load.
G	Gust factor.
h_R	Height of wind ribs.
H	Cooling tower height above basin sill level.
H_b	Vertical distance from the throat to basin sill level.
IL	Imposed load.
I_x	Moment of inertia of the un-cracked reinforced concrete cross-section of the upper edge beam about vertical centreline, in m^4.
l_{col}	Clear length of raker column.
l_{eff}	Effective length of raker column.
n_{min}	Lowest natural frequency, in Hz (normally this is ovaling mode).
p_{cr}	Critical dynamic wind pressure based on gust wind speed, in N/m^2 at throat level.
$\overline{p}_d$	Design hourly mean wind pressure.
$p_{(z,\theta)}$	Total peak wind pressure.
$q_b(H)$	Gust wind pressure based on gust wind speed at total height, H, in KN/m^2.
q_g	Gust wind pressure based on gust wind speed at throat height of tower.
r_H	Shell radius at upper edge, in m.
r_{th}	Throat radius, in m.
S	Shrinkage load.
t	Minimum shell thickness, in m.
T	Temperature load.
T_S	Summer temperature including solar radiation.
T_O	Casting temperature.
T_{op}	Operational temperature.
T_W	Winter temperature.
V_b	Basic wind speed.
WL	Wind load.
z	Height above ground.
β	Effective length factor for raker column in radial or tangential direction.
γ_B	Factor of safety against buckling.
υ	Poisson's ratio.
σ_ϕ	Coincident meridional compressive membrane stress.
$\sigma_{\phi,cr}$	Meridional critical stress, in N/m^2.
σ_θ	Coincident circumferential compressive membrane stress.
$\sigma_{\theta,cr}$	Circumferential critical stress, in N/m^2.
θ	Angular position measured from the incident wind direction, in degrees.
ΔT_m	Temperature difference between the inside and outside of the cooling tower shell.
ΔT_N	Temperature change at the middle surface of the shell.

5 ENVIRONMENTAL EXPOSURE CONDITIONS

Environmental exposure conditions shall conform to the same given in IS 456.

6 MATERIALS

6.1 Concrete

The materials for concrete shall conform to the requirements specified in IS 456 except stated otherwise in this standard.

6.2 Steel

The steel for reinforcement shall be any of the following:

a) Mild steel and medium tensile steel bars and hard-drawn, steel wire conforming to IS 432 (Part 1) and IS 432 (Part 2),
b) Hard-drawn steel wire fabric for reinforcement conforming to IS 1566,
c) High strength deformed bars (HYSD) conforming to IS 1786, and
d) High strength stainless steel reinforcement bars conforming to IS 16651.

6.3 Concrete Mix

Structural concrete shall be of design mix complying with the relevant provision of IS 456. The minimum grades of concrete for structural components shall be as follows:

a) M35 — For raker columns, shell, and ring beams.
b) M30 — For foundation, basin, basin wall, fill supporting structure and all other members.

6.4 Steel Work (Exposed)

In view of particularly severe wet and humid conditions in and around cooling towers, exposed steel work shall be used only for minor components and fixtures, such as doors, access ladders, handrail and the like. Such exposed steel work shall be given suitable and adequate protective treatment.

7 LOADING

7.1 The following loads shall be considered:

a) Dead loads;
b) Imposed loads
c) Wind loads;
d) Earthquake forces;
e) Thermal restraint/temperature loads;
f) Construction loads; and
g) Any other loads, such as snow loads, foundation settlement, etc.

7.1.1 *Dead Load (DL)*

Dead load shall be calculated from the actual weights of the materials used. Unit weight of materials shall be taken in accordance with IS 875 (Part 1).

7.1.2 *Imposed Loads (IL)*

Loads on the shell by permanent fixing shall be minimized. The local effects of the attachments on the structure should be accounted for. Imposed loads need not be considered in the global analysis of the tower shell, shell supports and shell foundation.

7.1.3 *Wind Load (WL)*

The effects of the wind load are to be determined by applying equivalent static wind load in terms of surface pressure. The applied equivalent static wind load includes the peak effect by means of gust factor which takes into account the gust effect of the pressure field on the cooling tower shell and the gust load behaviour of the cooling tower structure. The applied equivalent static wind load also includes the interference effect. The gust wind speed shall, in general, conform to basic wind speed V_b of IS 875 (Part 3) excepting in places where local conditions warrant special investigations.

The influence of the wind direction may be taken in to account in the determination of the wind pressure if secured statistical values on the wind rosette are available.

The wind pressure distribution is influenced by the roughness of the cooling tower surface. The roughness is created by ribs which can generally be implemented as pilaster strips for the climbing formwork and/or as additional wind ribs.

A difference is to be made between the wind pressure acting on the external surface of the cooling tower shell and the internal pressure acting on the internal surface. The total pressure coefficient acting on the shell is defined as the net difference between external and internal pressure coefficient. Pressure directed towards the shell surface is defined as positive.

In case the tower is located in cyclone prone zone as defined in IS 875 (Part 3), the cyclonic factor k_4, as applicable for industrial structures shall be used. For all other cases, it shall be 1.0.

7.1.3.1 The total peak wind pressure $p(z,\theta)$ can be obtained as:

$$p(z,\theta) = c_{p,\theta} F \; \overline{p}_d . G$$

where

$c_{p,\theta}$ = total pressure coefficient determined in accordance with **7.1.4;**

F = wind load amplification factor including dynamic amplification and interference effects as per **7.1.3.2** to **7.1.3.4**;

$\overline{p}_d$ = design hourly mean wind pressure as per IS 875 (Part 3); and

G = $G \approx 1 + g_v r \sqrt{B}$ gust factor as per **10.2** of IS 875 (Part 3) (a variable excludes resonant effect).

7.1.3.2 *Dynamic amplification*

Resonant vibrations caused by the fluctuating wind load component are taken into account by increasing the equivalent static load. The dynamic amplification factor, Fa, for shells with and without stiffening ribs may be taken as given in Table 1.

A uniform amplification factor as given in Table 1 is in general, is adequate. For unusual shell geometries and for more detailed investigations, a calculation in accordance with the theory of random vibrations may be made based on detailed stochastic dynamic behaviour with random dynamic wind load.

Table 1 Values of Dynamic Amplification

(*Clause* 7.1.3.2)

Sl No.	$\dfrac{q_b(H)\times 10^4}{(d_1 n_{min})^2}$	Dynamic Amplification Factor, F_a
(1)	(2)	(3)
i)	0	1
ii)	10	1.16

NOTE — Intermediate values can be calculated by linear interpolation.

7.1.3.3 *Interference effects*

If cooling towers or tall power plant buildings are in close vicinity to the cooling tower under construction as shown in Fig. 1, their flow fields will interfere with each other, altering the static and dynamic wind load as compared to an isolated tower. Consequently, increased stresses may occur depending on the type and distance of the adjacent cooling tower/building. The following points are to be considered:

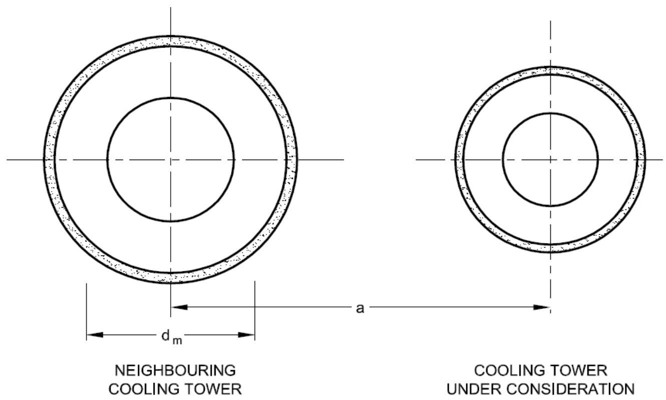
a) The interference effects are taken in to account by increasing the wind load (equivalent static load) for the isolated tower by an interference factor F_i, and if necessary, increasing the ratio of minimum reinforcement for the circumferential reinforcement in the lower half of the shell. The minimum reinforcement in the upper half of the shell need not be increased.

b) The amplified wind load has to be taken into account for the design of the tower and the supporting structure including the foundation, but not for the verification of the founding strata.

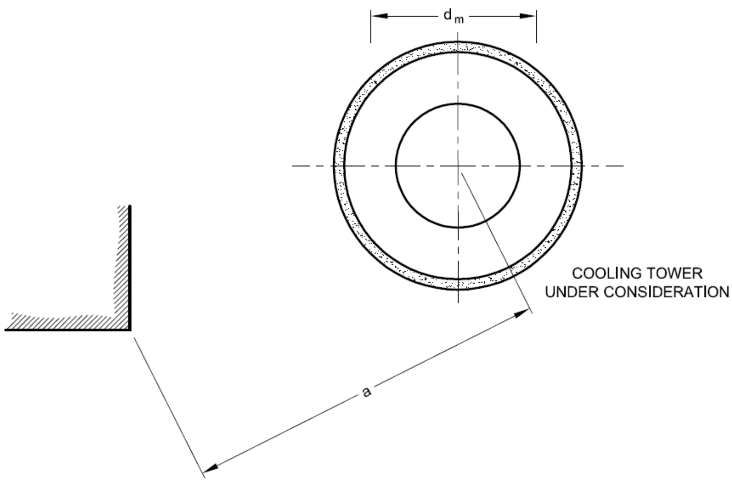
c) The interference factor is to be determined considering the distance parameter a/d_m and the type of the adjacent building. The average diameter, d_m of the shell is to be calculated as follows:

$$d_m = (d_u + d_T)/2$$

If the distance parameter a/d_m is greater than 4, then $F_i = 1$.



1A COOLING TOWER - COOLING TOWER INTERFERENCE



1B COOLING TOWER - BUILDING INTERFERENCE

Fig. 1 Interference Effects

If a/d_m is smaller than 1.6, no interference factor is specified. In this case more detailed investigations are recommended, for example, wind tunnel tests in a boundary layer wind tunnel.

If $1.6 < a/d_m < 4$, the interference factor, F_i, and the increase in the minimum reinforcement ratio in the circumferential direction are to be determined as described below:

$$F_i = 1 + 0.14\,(4 - a/d_m) \geq 1.0$$

$$\rho_r = 0.1\,[3.2 + (4 - a/d_m)/3.2] \text{ percent} \geq 0.32 \text{ percent}$$

d) The interference factor given here is also valid for groups of more than two cooling towers.

e) A interference factor may be neglected if the building height is less than 40 percent of the cooling tower height.

f) If the cooling tower is surrounded by several groups of tall buildings, a more detailed examination of the interference effects is necessary. If there is more than one interference situation, the most critical case is to be considered.

g) The interference factors may be disregarded if the static and dynamic effects of interference are investigated in more detail. In this case the influence of wind rose diagram may be taken in to account.

7.1.3.4 Wind load amplification factor can be calculated as follows:

$$F = F_a . F_i$$

7.1.4 The wind pressure coefficient distribution on the shell should preferably be derived from wind tunnel tests of a model of the proposed tower shell shape. As this is not normally practicable, the external wind pressure distribution suggested in Fig. 2 and total pressure distribution in Fig. 3 may be used for cooling towers built singly or in groups spaced, in accordance with **8.2**.

7.1.4.1 The surface roughness parameter h_R/a_R shall be taken as shown in Fig. 2 and Table 2, with average distance between the ribs a_R and the average height of the ribs h_R taken at one third of the shell height.

7.1.4.2 Each of the curve is described by three analytical functions as shown in Fig. 3. Table 3 additionally gives the expression for total pressure coefficient $C_{p,\theta}$ for the resulting wind force.

7.1.5 It is recommended that for towers of height greater than 120 m or built at closer spacing, wind pressure distribution shall be determined by aero-elastic model testing in atmospheric boundary layer wind tunnel offering appropriate aerodynamic similitude. Such models shall include all adjacent topographical features, buildings and other structures which are likely to influence the wind load pattern on the tower significantly. If pressures obtained from wind tunnel tests are higher than the pressures specified in this standard, the pressures obtained from wind tunnel tests shall be followed in the design.

Table 2 Minimum Pressure Coefficient and Distribution Curve

(*Clause* 7.1.4.1)

Sl No.	Surface	Roughness Parameter a_R/h_R	Minimum Total Pressure, $C_{p,\theta}$	Distribution Curve
(1)	(2)	(3)	(4)	(5)
i)	Without ribs	a) Smooth finish	-1.1	K1.6
		b) Off shutter finish	-1.0	K1.5
ii)	With ribs	a) 167 to 100	-0.8	K1.3
		b) 100 to 63	-0.7	K1.2
		c) 63 to 40	-0.6	K1.1
		d) 40 to 10	-0.5	K1.0

NOTE — Surfaces are considered to have an off-shutter finish, if uniformly distributed roughness dents with average heights greater than 5×10^{-5} times the average diameter of the shell d_m occur. In the case of smooth surface, pressure distribution curve K1.6 shall be used.

7.1.6 *Earthquake Forces (EQ)*

Earthquake forces shall conform to IS 1893 (Part 1) and IS 1893 (Part 4). It is recommended that analysis and design of tower shell, shell supporting structure and its foundation shall be carried out on the basis of modal analysis.

7.1.7 *Temperature Loads (T)*

Thermal loads on towers caused by solar radiation and operational temperature variations do not significantly affect the ultimate limit state. Normal serviceability requirements are met by the minimum reinforcement provided in the shell.

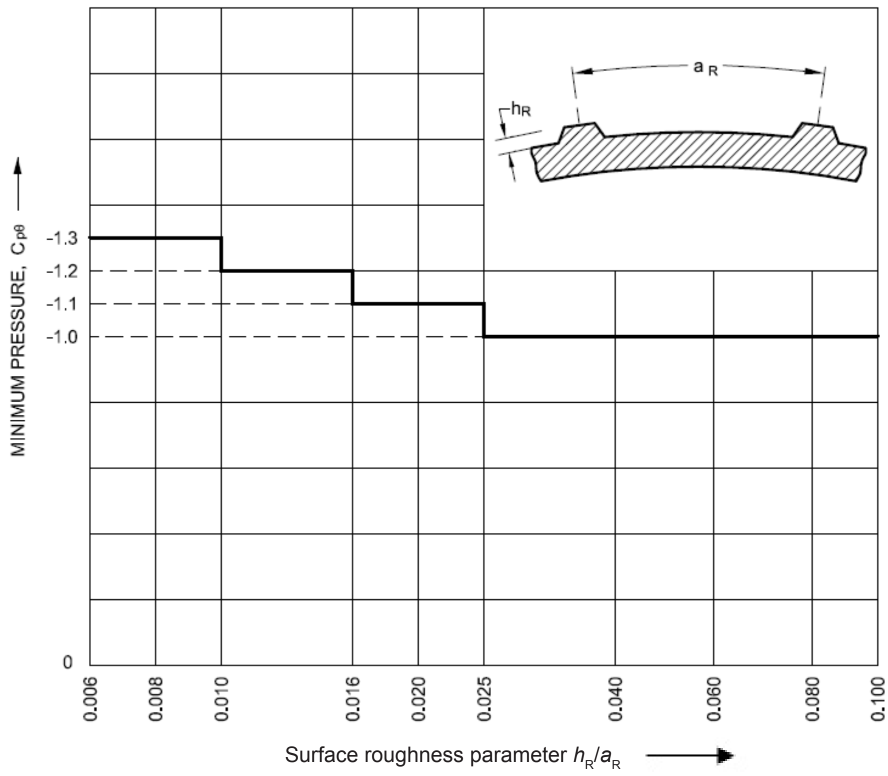


FIG. 2 MINIMUM EXTERNAL PRESSURE COEFFICIENT IN RELATION TO SURFACE ROUGHNESS

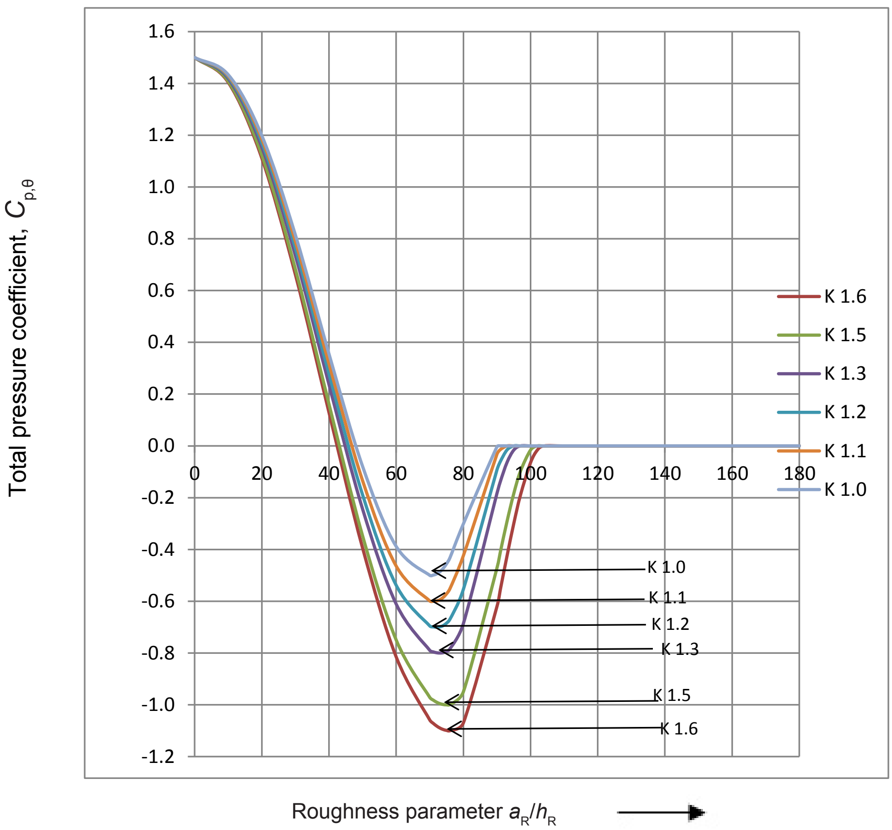


FIG. 3 TOTAL PRESSURE COEFFICIENT DISTRIBUTION, $C_{p,\theta}$

Table 3 Total Pressure Coefficient

(*Clause* 7.1.4.2)

Sl No.	Curve	Minimum Total Pressure Coefficient	Zone 1	Zone 2	Zone 3	C_f
(1)	(2)	(3)	(4)	(5)	(6)	(7)
(i)	K1.6	-1.1	0° ≤θ≤76° $1.5-2.6\left(\sin\frac{90}{76}\theta\right)^{2.085}$	76° ≤θ≤104° $-1.1+1.1\left[\sin\frac{90}{28}(\theta-76)\right]^{2.395}$	104° ≤θ≤180° 0	0.46
(ii)	K1.5	-1.0	0° ≤ θ≤ 75° $1.5-2.5\left(\sin\frac{90}{75}\theta\right)^{2.104}$	75° ≤ θ≤ 102° $-1.0+1.0\left[\sin\frac{90}{27}(\theta-75)\right]^{2.395}$	102° ≤ θ ≤180° 0	0.49
(iii)	K1.3	-0.8	0° ≤θ≤73° $1.5-2.3\left(\sin\frac{90}{73}\theta\right)^{2.166}$	73° ≤θ≤97° $-0.8+0.8\left[\sin\frac{90}{24}(\theta-73)\right]^{2.395}$	97° ≤θ≤180° 0	0.56
(iv)	K1.2	-0.7	0° ≤θ≤72° $1.5-2.2\left(\sin\frac{90}{72}\theta\right)^{2.205}$	72° ≤θ≤95° $-0.7+0.7\left[\sin\frac{90}{23}(\theta-72)\right]^{2.395}$	95° ≤θ≤180° 0	0.60
(v)	K1.1	-0.6	0° ≤θ≤71° $1.5-2.1\left(\sin\frac{90}{71}\theta\right)^{2.239}$	71° ≤θ≤93° $-0.6+0.6\left[\sin\frac{90}{22}(\theta-71)\right]^{2.395}$	93° ≤θ≤180° 0	0.64
(vi)	K1.0	-0.5	0° ≤θ≤70° $1.5-2.0\left(\sin\frac{90}{70}\theta\right)^{2.267}$	70° ≤θ≤91° $-0.5+0.5\left[\sin\frac{90}{21}(\theta-70)\right]^{2.395}$	91° ≤θ≤180° 0	0.66

7.1.7.1 For serviceability limit state, considerations shall be given to the following:

a) Distinction shall be made between the operational temperature T_{op}, summer temperature including solar radiation T_s, and winter temperature T_w. Effect of temperature change ΔT_N at the middle surface of the shell with respect to the casting temperature T_O and simultaneous temperature difference ΔT_m between the inside and outside of the cooling tower shell shall be considered in the design. ΔT_m is considered as positive when inside of the shell is warmer than the outside.

b) The minimum temperature of the outside atmospheric air T_{min}, maximum temperature of the outside atmospheric air, T_{max} and the reference temperature at the casting of the concrete should be considered. In absence of more precise data maximum and minimum ambient air temperatures may be taken from IS 875 (Part 5).

c) In the absence of project specific data, following values may be assumed:

   1) Maximum temperature of outside air T_{max} = 45°C.

   2) Minimum temperature of outside air T_{min} = 5°C.

   3) The reference temperature at the time of erection may be taken as T_O = 30°C.

7.1.7.2 *Operational temperature* (T_{op})

The effect of the operational temperature, T_{op} is critical during winter condition. The minimum outside air temperature, T_{min}, corresponding axially symmetrical maximum inside air temperature, T_i should be considered. Applicable values for the structural design shall be defined for a particular project.

Effective temperature difference (warmer on inside) within the cross section of the shell wall may be calculated as per Annex B. In absence of project specific data, maximum inside air temperature during winter T_i shall be taken as 15°C.

The design temperature conditions consist of a continuous temperature change $\Delta T_{N,OP}$ and a temperature difference $\Delta T_{M,OP}$. These may be calculated as follows:

$$\Delta T_{N,OP} = (T_i + T_{min}) / 2 - T_o$$

$$\Delta T_{M,OP} = T_i - T_{min}$$

Depending on the design of the water distribution system, transitional areas may lead to lower temperature effects in these areas of the shell. Allowance may be made for this.

7.1.7.3 *Summer temperature* (T_S)

This includes the effect of solar radiation. A temperature constant over the tower height is to be considered, which is composed of an axially symmetrical temperature change $\Delta T_{N,S}$ in the centre plane of the shell and of an temperature difference $\Delta T_{M,S,eff}$ described by a cosine function for half of the circumference (warmer on outside).

$$\Delta T_{N,S} = T_{max} - T_O$$

$\Delta T_{M,S,eff}$ = 15 °C (concrete temperature warmer on the outside)

Effective temperature difference (warmer on inside) within the cross section of the shell wall may be calculated as per Annex B.

7.1.7.4 *Winter temperature* (T_W)

For the winter condition only the temperature changes $\Delta T_{N,W}$ in the centre plane of the shell shall be taken in to account.

$$\Delta T_{N,W} = T_{min} - T_O$$

NOTE — The effect of solar radiation need not be considered as they have already been covered in summer condition.

7.1.8 *Foundation Settlement Load* (F_S)

Differential foundation settlement should be taken in to account in the analysis when same may occur within the shell support structure.

7.1.9 *Shrinkage Load (S)*

Equivalent temperature change of 15°C in the centre plane of the shell shall be considered.

7.1.10 *Construction loads*

Loads acting during construction shall be taken in to consideration in the design. Construction loads may include the following:

a) Transportation of concrete;
b) Scaffolding and formwork;
c) Hoist fixing;
d) Storage of materials on scaffold; and
e) Tower crane fixing.

7.2 Load Combinations

The combination of different loads for design purposes shall be in accordance with IS 875 (Part 5).

7.2.1 *Ultimate Limit State*

Following load combinations shall be considered:

$$1.0\ DL + 1.5\ WL$$

$$1.4\ DL + 1.5\ WL$$

7.2.2 *Serviceability Limit State*

Under serviceability limit state calculated maximum crack width should not exceed 0.3 mm. However, where cooling water carries constituents aggressive to reinforced concrete, calculated crack width in shell should be limited to 0.2 mm. Also where stainless steel is used as reinforcement, crack width may be 0.3 mm.

Following load combinations for serviceability consideration shall be considered.

$$DL + 0.5\ WL + 0.5\ T_{OP}$$

$$DL + 0.5\ WL + 0.5\ T_{OP} + S + F_s$$

$$DL + 0.7\ T_{OP} + S + F_s$$

$$DL + 0.5\ T_s + S + F_s$$

$$DL + 0.5\ T_W + S + F_s$$

Effect of T_{OP}, S and F_s shall be considered when their effects are unfavourable.

7.3 Partial safety factors for loads and materials shall be considered as specified in IS 456.

8 TOWER DESIGN CONSIDERATIONS

8.1 Size and Shape

The base diameter, air intake, opening height, tower height and throat diameter are determined by thermal design considerations. The details of a typical hyperbolic counter flow cooling tower is given in Fig. 4.

8.1.1 As the range of possible hyperbolic shell shapes is infinite it is recommended that the designs be confined to the following major proportions which have been extensively adopted in cooling tower constructions. Other proportions shall be carefully studied before adoption:

$$H/D = 1.20 \text{ to } 1.55$$

$$H_b/H = 0.75 \text{ to } 0.85$$

8.1.2 The minimum thickness of the shell shall not be less than 200 mm.

8.2 Spacing

It is recommended that the cooling towers in a group be spaced at clear distance of not less than 0.5 times the base diameter of the largest cooling tower in the group. Even at this spacing, aerodynamic interference occurs and the design recommendations given in this standard takes this into account.

8.3 Tower Shell

8.3.1 *Shell Analysis*

8.3.1.1 Analysis shall be carried out using a shell theory based on bending analysis. Linear elastic analysis assuming small shell deformations are acceptable.

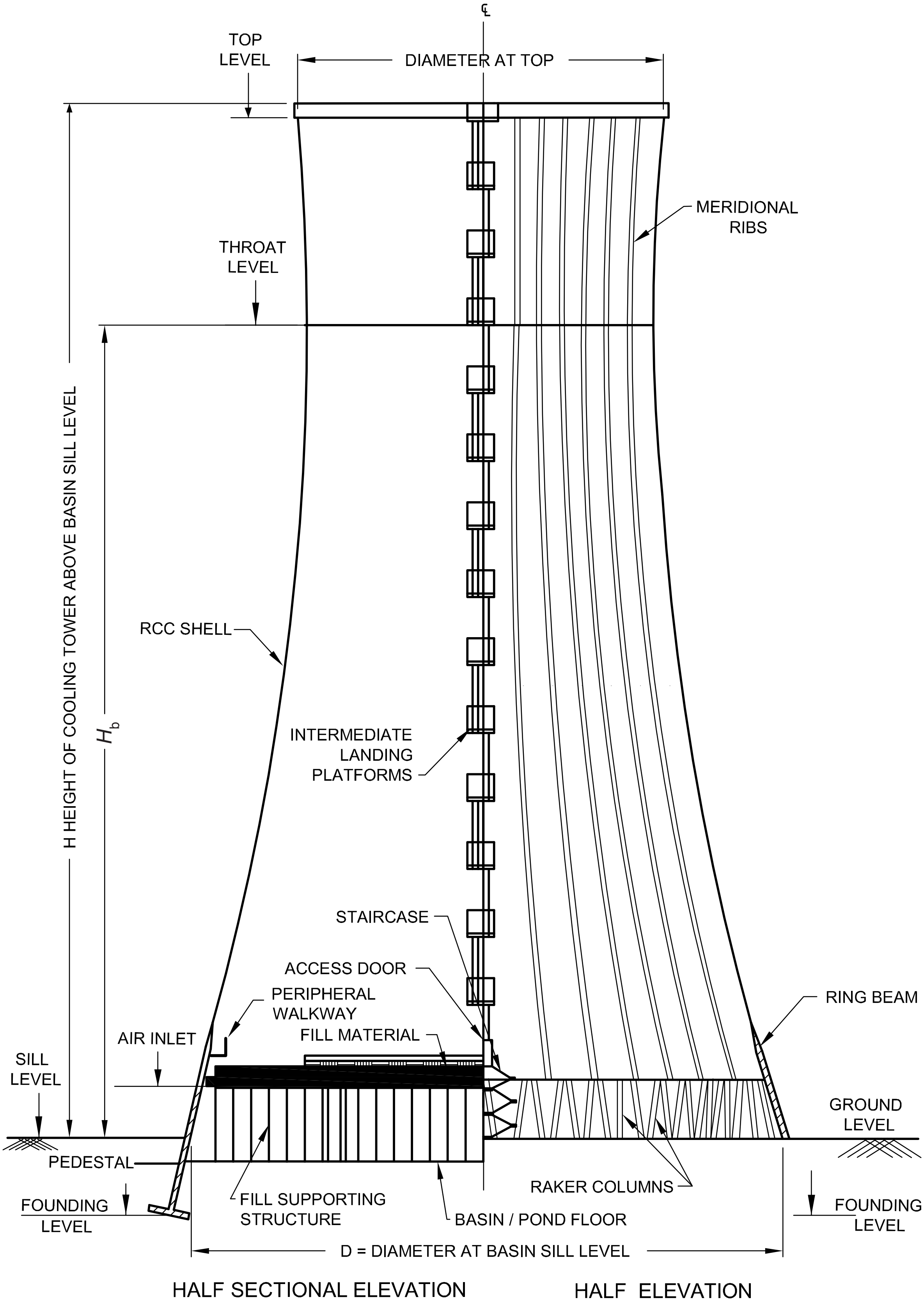


FIG. 4 DETAILS OF A TYPICAL HYPERBOLIC COUNTERFLOW COOLING TOWER

Alternatively, non-linear calculations using non-linear material properties with cracking and post cracking behaviour taking in to account the relevant concrete tensile stiffness and the possible influence of large deformations may be performed.

8.3.1.2 A proven finite element method (FEM) is recommended. The lower and upper edge portion, shell supporting raker columns and the foundation shall be considered with realistic stiffness values. Non-uniform subsoil properties along with periphery of foundation and their interaction with the cooling tower structure shall be taken into account.

8.3.1.3 The following boundary conditions may be assumed for the normal range of provisions in the design of cooling tower shells:

a) *At upper edge* — The top edge of the shell is often thickened to form a ring beam, but is generally considered as a free edge in the analysis. It is recommended that the thickness transition from shell to upper ring beam should be smooth. In absence of detailed investigation, following criteria shall be satisfied.

$$I_x / r_H = 0.003 \text{ m}^3$$

b) *At lower edge* — The lower edge of the shell is always thickened to form a substantial lower ring beam. It is recommended that the thickness of the transition from shell to lower ring beam is smooth and considered as an integral part of the shell. It is recommended that the lower boundary of the shell may be considered as elastically supported by the columns.

8.3.2 *Buckling of Tower Shells*

8.3.2.1 *Snap through buckling of the shell*

Analysis of the buckling safety may be carried out by applying numerical methods according to classical theory of stability, considering realistic stiffness of the cooling structure as a whole. Critical dynamic pressure (wind pressure) at buckling from tests on hyperbolic shell models may be approximated by equation given below:

$$p_{cr} = 0.052 E_c \left(\frac{t}{r_{th}} \right)^{7/3} \times 10^6$$

The factor of safety against buckling γ_B, is given by:

$$\gamma_B = \frac{p_{cr}}{q_g}$$

A factor of safety of 5 is recommended for critical buckling pressure.

8.3.2.2 *Local buckling of the shell*

The factor of safety against local buckling shall be carried out for load combination (DL + WL) using following equations:

$$\sigma_{\theta,cr} = \frac{0.985 E_c}{\left(1-\upsilon^2\right)^{3/4}} \left(\frac{t}{r_{th}} \right)^{4/3} \lambda_\theta \times 10^6$$

$$\sigma_{\phi,cr} = \frac{0.612 E_c}{\left(1-\upsilon^2\right)^{3/4}} \left(\frac{t}{r_{th}} \right)^{4/3} \lambda_\phi \times 10^6$$

where,

λ_θ and λ_ϕ are given in Table 4. Intermediate values can be interpolated. In the Table 4, R_B is the radius at the underside of the ring beam (in m), R_T is the radius at the underside of the ring beam at the hight of throat (in m) and Z_T is the height of the throat above the underside of the ring beam (in m).

The factor of safety against local buckling γ_B can be found by using following equation:

$$0.8\gamma_B \left(\frac{\sigma_\theta}{\sigma_{\theta,cr}} + \frac{\sigma_\phi}{\sigma_{\phi,cr}} \right) + 0.2\gamma_B^2 \left\{ \left(\frac{\sigma_\theta}{\sigma_{\theta,cr}} \right)^2 + \left(\frac{\sigma_\phi}{\sigma_{\phi,cr}} \right)^2 \right\} = 1$$

The value of tensile stress in above formulae should be taken as zero. Factor of safety should be greater than 5 at any point in the shell.

Table 4 Values of λ_θ and λ_ϕ

(*Clause* 8.3.2.2)

R_T/R_B	λ_θ			λ_ϕ		
	R_T/Z_T = 0.250	R_T/Z_T = 0.333	R_T/Z_T = 0.416	R_T/Z_T = 0.250	R_T/Z_T = 0.333	R_T/Z_T = 0.416
0.571	0.105	0.162	0.222	1.28	1.20	1.13
0.600	0.102	0.157	0.216	1.33	1.25	1.17
0.628	0.098	0.150	0.210	1.37	1.30	1.23
0.667	0.092	0.138	0.198	1.45	1.37	1.31
0.715	0.081	0.124	0.185	1.56	1.49	1.43
0.800	0.063	0.096	0.162	1.74	1.73	1.68
0.833	0.056	0.085	0.151	1.85	1.85	1.82

8.3.3 *Foundation Lift Off*

The foundation lift off is defined as the condition when the uplift (tensile) forces on any discrete element of the shell support structure, derived by linear elastic analysis of tower structure, equals or exceeds the dead weight of the support structure, and its base, plus the permissible capacity of any anchorage system provided, for example, ground anchors, rock anchors, tensile piles, etc. The tower design shall be checked against lift off using following criteria:

a) Under the loading 1.0 *DL* + 1.0 *WL*, no lift off should occur.

b) In absence more detailed analysis including non-linear analysis considering loss of support due to an uplift, under the loading 1.0 *DL* + 1.5 *WL*, the arc over which lift off occurs, if any, should not exceed 30° of the circumference of the tower.

The structural interaction should also be considered in case of loss of support due to an uplift of an isolated foundation or sector of ring foundation. The consideration of a local loss of support can be replaced by an appropriate assumption of stress redistribution in the structural modelling.

8.3.4 *Openings in Shells*

Opening through the shells shall be avoided as far as possible. They should be of smallest required dimensions and shall be shaped such that stress concentration is minimized at the boundary of the opening. Should thickening of the edges be necessary, it shall be smoothly tapered back to the shell thickness. The shell analysis shall take account of openings having any dimension greater than 2.1 m.

Openings shall be provided with additional edge reinforcements of a minimum cross-sectional area at each edge equal to 75 percent of the reinforcement intercepted by the openings in the direction parallel to the edges. In addition, diagonal reinforcement shall be provided at each corner as close as possible. The total cross-sectional area, in mm^2 of this reinforcement shall be 5 *d*, at each corner where, *d* is the shell thickness, in mm.

No horizontal thrust due to inlet piping shall be transmitted to the shell.

8.3.5 *Placement and Spacing of Reinforcement*

The minimum cold worked high yield strength deformed (HYSD) reinforcement of 0.30 percent of the concrete cross sectional area shall be provided in each direction. Minimum reinforcement in circumferential direction in top one third of the shell shall be 0.40 percent of the concrete cross-sectional area.

The maximum spacing shall be restricted to twice the thickness of the shell or 250 mm for vertical reinforcement between the circumferential reinforcement and 300 mm spacing between the meridional reinforcement, whichever is the less. Reinforcement shall be provided on each face of the shell in each direction.

8.3.6 *Cover*

The two layers of reinforcement are provided. The clear cover to main reinforcement shall not be less than 30 mm. This cover of minimum 30 mm needs rigorous control on steel positioning, concrete quality and concrete compaction. In special cases of aggressive conditions, the cover shall be increased as per IS 456 or suitable and adequate protective treatments shall be provided.

8.3.7 *Reinforcement Splices*

The splices of the reinforcing bars shall be staggered as per IS 456. Not more than 50 percent of the bars shall be spliced at any location cross-section in the circumferential and meridional direction.

8.4 Shell Supporting Structure

The dead weight of the integral shell and the wind or seismic forces induced in it are transmitted to the foundation system through a series of raker columns spanning air intake openings. It is recommended that the inclination of these columns closely matches the meridional slope at the base of the integral shell so that the load transfer to foundation takes place through predominantly axial forces in columns. The columns shall be designed as per IS 456. Effective length of the raker column $l_{eff} = \beta\, l_{col}$ shall be considered as follows taking in to account fixing of the raker column in the shell and foundation:

Description	*Factor β in Radial Direction*	*Factor β in Tangential Direction*
Column fixed at both ends	0.8	0.6
Column fixed at one end	0.9	0.7

8.5 Foundations and Auxiliary Structures

Analysis, design, and construction of foundation and auxiliary structures, such as basin, supporting structures for packing, platforms, internal grillage, etc, shall be in accordance with the following Indian Standards as may be applicable:

Foundations	IS 2911 (Part 1/Sec 1),
	IS 2911 (Part 1/Sec 2),
	IS 2911 (Part 1/Sec 3), and
	IS 2950 (Part 1)
Platforms/internal grillage	IS 456
Basin distribution ducts	IS 3370 (Part 1)
	IS 3370 (Part 2)
	IS 3370 (Part 3)
Steel structures	IS 800

8.5.1 When the tower is supported on pile foundation, the necessity or otherwise of providing raker piles to resist horizontal forces may be investigated. Influence of foundation settlement, if any, shall be taken into account while designing the tower shell, raker columns and foundations. It is recommended that in

the analysis soil structure interaction may be taken into account.

8.5.2 If the tower is more than 75 m high, continuous foundations or continuous annular pile cap may be provided. For smaller towers, individual isolated foundations may be adopted.

9 CONSTRUCTIONAL ASPECTS

9.1 General

The setting out, checking and formwork system shall be intended to produce smooth surface, without geometrical deformities. It shall also produce a high degree of dimensional accuracy to ensure the design considerations originally envisaged.

9.2 Basic Construction Plan

9.2.1 A basic construction plan shall be prepared for the cooling tower shell and shell supports. The plan shall include the following elements, and any other information relevant to the construction of shell and columns:

a) Method statement for operation of climbing rigs, if used, hoisting equipment, etc.
b) Criteria for removal of formwork and imposition of construction loads.
c) Method of transporting concrete to working levels.
d) Setting out methods with details of any instrumentation to be used.
e) Type and make-up of formwork to be used on the tower shell.
f) Method of storing and curing concrete test cubes.

9.2.2 The plan shall include key values, required by the method of working, for the following items:

a) Minimum concrete strength for the operation of climbing access rigs and/or hoisting equipment attached or supported by the partially completed structure,
b) Minimum concrete strength of previous lift for pouring of fresh concrete in successive lift.

9.3 Requirements for construction of shell are as follows:

a) The shell support columns shall be cast in position or located in position if precast. They shall be supported by temporary propping, such that the deflection of column heads, subjected to temporary works loading, does not exceed 5 mm.
b) No props shall be removed until a complete lift of the ring beam, not less than 1 m depth, has been cast and has attained a compressive strength, as determined by match cured test cubes, of not less than 20 *N/sq.mm* (reference can be made from IS 456).
c) No climbing rigs, hoisting equipment, etc. shall be attached to the shell within 36° arc from a stop end until the first lift of the ring beam is completed.
d) The striking of formwork shall only be carried out when the concrete has reached an appropriate maturity level.
e) The operations of pouring fresh concrete and of moving climbing rigs and/or hoisting equipment shall be governed by the results of match cured compressive test cubes.

NOTE — A match cured test cube is defined as a cube that is manufactured, stored, cured and tested in such a way that it realistically reflects the behaviour of the parent concrete.

f) At least four test cubes shall be made from samples taken at the point of discharge in to the formwork at locations diametrically opposite to each other in any lift pour.
g) These cubes shall be taken at-least once every two lifts or every 3 m of shell height, whichever is lesser.
h) Two test cubes shall be match cured for a period of time considered to be representative of the pouring cycle.
j) One of the match cured cubes shall be crushed, if its compressive strength falls below the key value given in the basic construction plan for the operation of pouring fresh concrete, then after an appropriate period of time the second cube should be crushed. No further, concrete shall be poured until the concrete in the corresponding lift has achieved sufficient strength to withstand any loads which are to be imposed upon it.
k) The two remaining test cubes shall be match cured for a period of time representative of the rig moving cycle and should then be tested.
m) If the compressive strength of either cube falls below the key value given in the basic construction plan for the operation of moving climbing rigs and/or hoisting equipment, no lifting operation shall be carried out until the concrete in the lift which is required to withstand the loading from rig and/or hoisting equipment has achieved sufficient strength to do so.

9.4 Shell Formwork

The formwork for shell shall be capable of adjusting to shell profile and thickness accurately, and rigidly braced to prevent deflection or movement during concreting.

To achieve high dimensional accuracy, the formwork shall be rigid, shape preserving, tight fitting and easy to construct. The use of steel formwork is recommended at present. Except where recommended otherwise in this standard, provisions of IS 456 shall apply to formwork for cooling towers.

The shell wall concrete shall have sufficient strength to resist the anchor loads of the scaffolding system. During the climbing process, measures shall be taken to assure that the necessary concrete strength is always

reached. The results of the testing shall be properly documented.

The connections and joints between individual scaffolding units shall be designed, in such a way that an assumed collapse of one unit can not cause further units to collapse. Independent safety devices shall be implemented to prevent the collapse of the scaffolding unit during the climbing process.

9.5 Tolerances

Dimensional tolerances within which the construction be carried out shall be as follows:

a) The thickness of the finished concrete in the shell shall not vary from the design thickness by more than ± 6 mm.
b) The interior surface of the shell shall not vary from its stipulated position by more than ± 40 mm.
c) The measured offset from any 3 m chord shall not differ from the theoretical offset by more than ± 10 mm.
d) In the line of shell in the vertical plane, the shell shall not change direction, other than to form the curve of the tower, by more than 10 mm in any 1m slant height.
e) Horizontal radius at shell base shall not vary by more 0.005 times the support height but not more than ± 40 mm.
f) Foundation in radial and tangential direction shall not vary more than ± 60 mm.

9.6 Checking of Shell Geometry

The shell shall be surveyed at the appropriate level after the completion of each lift. Readings shall be taken in at-least one position on each primary formwork unit.

10 BASIN, FILL SUPPORTING STRUCTURE, WATER DISTRIBUTION SYSTEM

10.1 Fill supporting structure shall be designed as per IS 456 and water retaining structures like basin floor, basin walls, etc as per IS 3370 (Part 1), IS 3370 (Part 2) and IS 3370 (Part 3).

10.2 Stability against buoyancy shall be ensured by providing factor of safety as per IS 3370 (Part 1).

10.3 If the basin slab is designed with raft foundation, realistic soil stiffness should be considered in the analysis to transfer the loads.

10.4 In case of pile foundations the basin slab should be designed as a self-supporting structure. If effects of subsoil cannot be completely excluded, the possible subsoil contact pressure shall be considered in the design.

10.5 The basin slab, basin wall and cold water outlet shall be designed to ensure water tightness. The maximum calculated width of the cracks shall not exceed 0.2 mm

10.6 The minimum thickness of the basin wall and slab shall be 180 mm.

11 FITTINGS AND FIXTURES

11.1 Cooling tower fittings shall be designed for durability considering corrosive service conditions within the cooling tower. Adequate durability measures should be considered as per the relevant code.

11.2 Suitable gates may be used to isolate the cold water basin of large towers. They shall be designed to fit in to guides fixed in to the cold water channel to provide a seal for water pressure from either side.

11.3 Coarse screens should be designed to resist water pressures occurring with at least 25 percent of the screen free area blocked. Provisions shall be made for their removal for cleaning.

11.4 Every cooling tower shall have a complete system of lightening protection in accordance with the provision of IS 2309. In addition, it is recommended that vertical bars be tied to horizontal bars and the system suitably earthed.

11.5 External protective systems are not normally required for concrete cooling tower shells. Sufficient protection is considered to be provided by the existing reinforcement provided that good contact is maintained between reinforcement bars through fixing with tying wire as follows,

a) between lapped vertical bars;
b) between vertical and horizontal bars; and
c) between the reinforcement in the shell and the supporting ring beam and column bars.

An earthing check shall be carried out to examine whether additional lightening protection is required.

11.6 Aviation Warning System

Towers are usually tall and necessary aviation obstruction lighting (AOL) shall be provided as per the requirements of Annexure 14 to the Convention on International Aviation of International Civil Aviation Organization (ICAO) and those prescribed by Directorate General of Civil Aviation (DGCA).

ANNEX A

(*Clause* 2)

LIST OF REFERRED INDIAN STANDARDS

IS No.	*Title*
432	Mild steel and medium tensile steel bars and hard-drawn steel wire for concrete reinforcement
(Part 1) : 1982	Mild steel and medium tensile steel bars
(Part 2) : 1982	Hard-drawn steel wire
456 : 2000	Plain and reinforced concrete — Code of practice (*fourth revision*)
800 : 2007	General construction in steel — Code of practice (*third revision*)
1566 : 1982	Hard-drawn steel wire fabric for concrete reinforcement
875	Code of practice for design loads (other than earthquake) for buildings and structures
(Part 1) : 1987	Dead loads (*second revision*)
(Part 2) : 1987	Live loads (*second revision*)
(Part 3) : 2015	Wind loads (*third revision*)
(Part 4) : 1987	Snow loads (*second revision*)
(Part 5) : 1987	Special loads and combinations (*second revision*)
1786 : 2008	High strength deformed steel bars and wires for concrete reinforcement — Specification
1893	Criteria for earthquake resistant design of structures
(Part 1) : 2016	General provisions and buildings
(Part 2) : 2014	Liquid retaining tanks
(Part 4) : 2005	Industrial structures including stack-line structures
2204 : 1962	Code of practice for construction of reinforced concrete shell roof
2210 : 1988	Criteria for design of reinforced concrete shell structures and folded plates
2309 : 1989	Practice for the protection of buildings and allied structures against lighting — Code of practice
2911	Design and construction of pile foundations — Code of practice
(Part 1/ Sec 1) : 2010	Driven cast *in-situ* concrete piles
(Part 1/ Sec 2) : 2010	Bored cast in-situ concrete piles
(Part 1/ Sec 3) : 2010	Driven precast concrete piles
2950 (Part 1) : 1981	Code of practice for design and construction of raft foundations: Part 1 Design
3370	Concrete structures for storage of liquids — Code of practice
(Part 1) : 2020	General requirements
(Part 2) : 2020	Plain and reinforced concrete structures
(Part 3) : 2020	Prestressed concrete structures
16651 : 2007	High strength deformed stainless steel bars and wires for concrete reinforcement — Specification

ANNEX B

(*Clauses* 7.1.7.2 *and* 7.1.7.3)

TEMPERATURE PROFILE ACROSS SHELL THICKNESS

B-1 Temperature profile may be determined using the thermal transmission theory. In the case of slab, wall and shell temperature profile may be worked out under the assumption that local thermal bridges do not exist. A temperature T(x) at a distance, x, from the inner surface of the cross section may be determined assuming steady thermal state as follows:

$$T(x) = T_{in} - \frac{R(x)}{R_{tot}}(T_{in} - T_{out})$$

where

T_{in} = air temperature of the inner environment;

T_{out} = temperature of the outer environment ($T_{in} > T_{out}$);

R_{tot} = total thermal resistance of the element including resistance of both surfaces; and

R(x) = thermal resistance at the inner surface and of the element from the inner surface up to the point x (*see* Fig. 5).

B-2 The resistance R_{tot} and R (x) (m^{2}K/W) may be determined using the coefficient of heat transfer and coefficients of thermal conductivity as follows:

$$R_{tot} = R_{in} + \sum_i \frac{h_i}{\lambda_i} + R_{out}$$

where

R_{in} = thermal resistance at the inner surface (m^{2}K/W);

R_{out} = thermal resistance at the outer surface (m^{2}K/W);

λ_i = thermal conductivity (W/mK); and

h_i = thickness of the layer i (m)

$$R(x) = R_{in} + \sum_i \frac{h_i}{\lambda_i}$$

Where, layers (or part of a layer) from the inner surface up to point x (*see* Fig. 5) are to be considered.

NOTES — In absence of more precise data, following values may be used.

a) The thermal resistance R_{in} = 0.10 to 0.17 (m^{2}K/W) (depending on the orientation of the heat flow) and R_{out} = 0.04 (m^{2}K/W) for all orientations.

b) The thermal conductivity λ_i for concrete (of weight density from 21 to 25 KN/m^3) varies from 1.16 to 1.71 (W/mK).

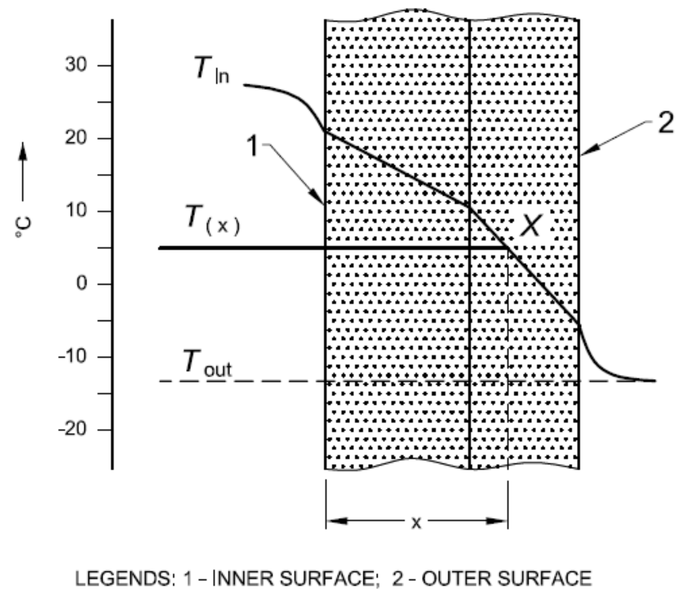


Fig. 5 Thermal Profile of Shell Element

ANNEX C

(*Foreword*)

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Review of Indian Standards

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